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*A LABORATORY INVESTIGATION
OF
PAVEMENT SLIPPERINESS
DEC., 1958
NO. 32*

by

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*Joint
Highway
Research
Project*

PURDUE UNIVERSITY
LAFAYETTE INDIANA



Technical Paper

TO: K. B. Woods, Director
Joint Highway Research Project

FROM: H. L. Michael, Assistant Director
Joint Highway Research Project

December 18, 1958

File: 9-6-4
Project: C-36-53D

Attached is a technical paper entitled, "A Laboratory Investigation of Pavement Slipperiness." This paper has been prepared by Mr. J. W. Shupe and Prof. W. H. Goetz of our staff.

This paper is a summary of the research conducted by Mr. Shupe under the supervision of Professor Goetz. The paper is proposed for presentation at the annual meeting of the Highway Research Board meeting in January 1959.

The paper is presented for the record.

Respectfully submitted,

H. L. Michael

H. L. Michael, Secretary

HLM:acc

Attachment

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Technical Paper

A LABORATORY INVESTIGATION OF PAVEMENT SLIPPERINESS

by

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Joint Highway Research Project
File No: 9-6-4
Project No: C-36-53D

Purdue University
Lafayette, Indiana
December, 1958

Prepared for Presentation at the
36th Annual Meeting of the Highway Research Board
January 5-9, 1959, Washington, D. C.

Not for Publication

(Subject to Change Before Publication)



A LABORATORY INVESTIGATION OF PAVEMENT SLIPPERINESS

J. W. Shupe¹ and W. H. Goetz²

Experience indicates that highways which are constructed to conform to current design standards may become dangerously slippery when wet after a relatively short period of wear. As the polishing effect of traffic continues to become more intensified, the incidence of slippery sections of pavement will tend to increase. In order to minimize the occurrence of these skidding hazards, the highway engineer must include permanency of skid resistance as a design parameter in selecting a suitable paving mixture.

A laboratory testing procedure was developed at Purdue University to investigate the slipperiness potential of different highway materials, and to predict the resistance of paving mixtures to the polishing effect of simulated traffic. The laboratory testing method, a field correlation study, and an accelerated wear and polish procedure are summarized in this report, along with the results of the initial phases of the research which have been reported upon previously (7). Included in this summary are 1) a report of the polishing characteristics of aggregates in both portland-cement and bituminous mixtures and 2) a study of the effect of surface texture, or degree of openness, and initial aggregate shape on the skid resistance of bituminous mixtures. A more complete discussion is presented of subsequent research in which

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the effect of blending a polish-resistant material with a polish-susceptible aggregate in both portland-cement and bituminous mixtures was determined, and of a study in which the anti-skid characteristics of fine-grained surface treatments were investigated. A final summary is presented which includes the authors' recommendations with regard to design and construction practices that tend to minimize pavement slipperiness.

LABORATORY SKID-TEST APPARATUS

The laboratory test procedure was developed to evaluate the skid resistance of portland-cement or bituminous specimens molded in the laboratory or cored from the pavement surface. The laboratory skid-test apparatus spins a 6-inch diameter test specimen at a constant speed of 2500 rpm and measures the skid resistance by forcing a rubber testing shoe against the surface of the test specimen with a unit pressure of 28 psi. The amount of torque developed in the shaft supporting the testing shoe due to the skidding action of the shoe on the test specimen, is automatically recorded as a measure of the skid resistance of the specimen. All tests were performed with the surface in the wet condition.

The skid resistance of each specimen was expressed as a relative resistance value (RRV), with Kentucky rock asphalt, which from field studies (1,2) has consistently exhibited excellent resistance to skidding, selected as the reference non-skid material. The skid-test apparatus was adjusted so that a Kentucky rock asphalt specimen cored from the highway surface gave an RRV of 1.00; and the relative skid resistance of the other surface types, based on an RRV of unity for Kentucky rock asphalt, was determined to the nearest 0.01. A complete discussion of the laboratory skid-test apparatus is presented

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in reference (5).

A field correlation study was performed on 17 bituminous and 9 portland-cement concrete test sections, all evaluated with the surface in a wet condition. Three stopping-distance tests were made on each of the sections by locking the wheels of the test vehicle at a speed of approximately 34 mph and measuring the distance required to skid to a complete stop. The average coefficient of friction was calculated by substituting in the standard stopping-distance equation:

$$s = \frac{V^2}{30 f}$$

where:

s = total stopping distance in feet,

V = initial speed of vehicle in mph,

f = average coefficient of friction over entire speed range of from V to 0 mph.

Three 6-inch diameter cores also were taken from each test section and evaluated in the laboratory skid-test apparatus. The results of a comparison of the field and laboratory methods of evaluating skid resistance are summarized in Fig. 1. Each plotted point represents the average coefficient of friction computed from the stopping distances of three lock-wheel tests performed on the highway, and the average RRV for three cores obtained from the test area and evaluated in the laboratory skid-test apparatus.

There was fairly good agreement between the field and laboratory methods of evaluating skid resistance, as shown in Figure 1. It was felt that a towed-vehicle type of field test (3, 8) which, like the laboratory test apparatus, measures skid resistance at constant speed would have resulted in a better correlation than the stopping-distance method. Unfortunately, such a unit was not available for

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this study. A detailed discussion of factors contributing to the variation in results between the field and laboratory methods of evaluating slipperiness is presented in reference (5). A consideration of these factors led to the conclusion that such discrepancies as exist tend to favor the laboratory method as giving a more realistic evaluation of slipperiness of wet surfaces than the stopping-distance method for speeds of 30 mph and upward.

ACCELERATED WEAR AND POLISH PROCEDURES

The primary criterion in selecting a standard laboratory specimen and in developing an accelerated wear and polish procedure was to simulate the surface characteristics that a similar mix would exhibit after an appreciable amount of highway service under the action of heavy traffic. The aggregate gradations for the standard laboratory specimens are listed in Table 1. For the standard asphaltic-concrete test specimen the asphalt content was kept intentionally low to emphasize the effect of the aggregate. The standard portland-cement concrete specimen was designed with a high cement factor and sufficient water to result in a slump of approximately 1 to 2 inches. To facilitate a comparison of the polishing characteristics of the various aggregates, each portland-cement and bituminous test specimen was composed entirely of one aggregate, except for that phase of the study in which blending of aggregates was investigated.

The bituminous specimens were vibrated to accomplish initial compaction, rolled with conical rollers to simulate the surface aggregate orientation that occurs on the highway, subjected to a coarse-wear cycle in which crushed quartz was used as the abrasive, given a fine-polish cycle with limestone mineral filler as the abrasive, and rolled again

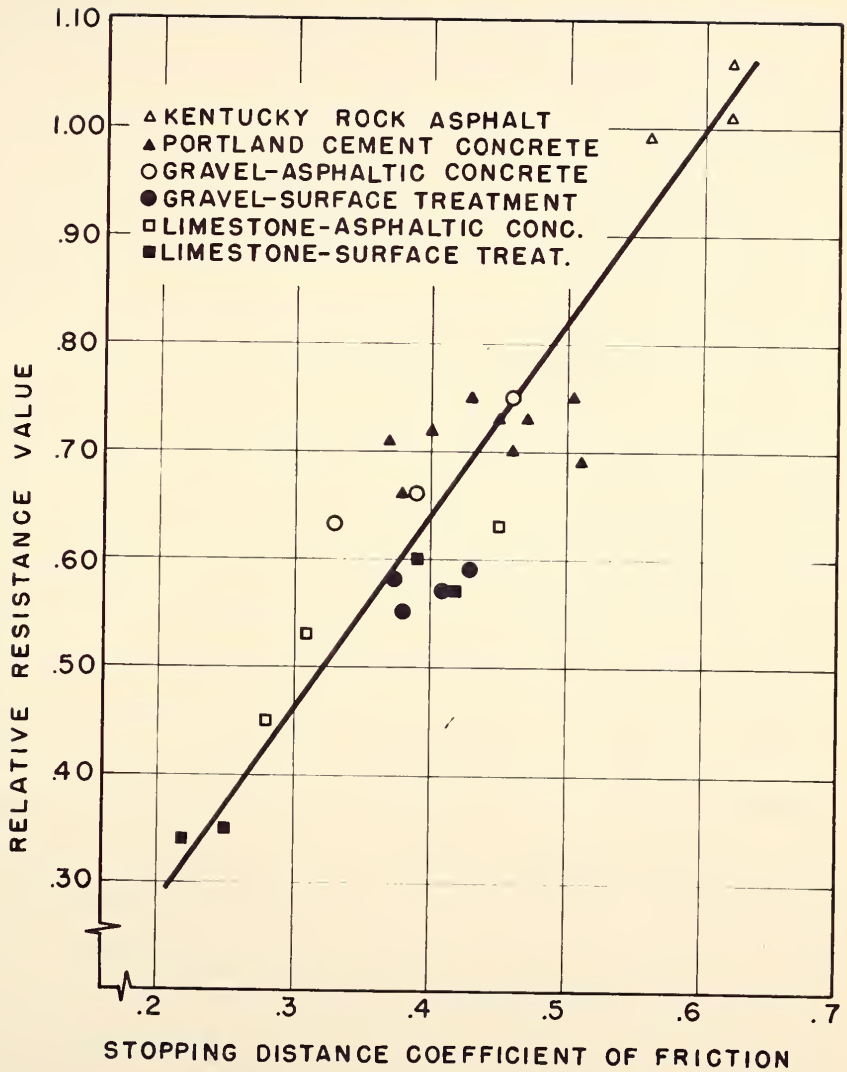


FIG.1 COMPARISON BETWEEN FIELD AND
LABORATORY SKID - TEST MEASUREMENTS

to coat the surface aggregate with a light film of asphalt. The variation in skid resistance of three typical bituminous mixtures due to this wear and polish procedure is illustrated in Figure 2. The relative resistance values are plotted as the ordinate with the position in the wearing cycle indicated along the abscissa. The initial RRV's were determined after the specimens had been vibrated, and the other four points correspond to values determined immediately following 1) initial rolling, 2) coarse polish, 3) fine polish, and 4) final rolling.

These three curves illustrate the excellent resistance to polishing of bituminous mixtures containing sandstone, as compared to specimens composed of rhyolite, which exhibit fair polishing resistance, or to mixtures made with oolitic limestone, which polished quite readily. In comparing the characteristics of the different specimens, the results determined at the completion of the fine-polish cycle (Wear cycle No. 3 of Fig. 2) are probably the most significant. At this point in the wearing procedure the test specimen possesses a clean surface with a texture similar to that of a well-worn bituminous pavement. The subsequent rolling operation was intended to indicate the susceptibility of the mixture to the loss in skid resistance which occurs due to the road film that accumulates on some highways during certain seasons of the year.

The portland-cement test specimens were subjected to a somewhat different procedure. During the finishing operation, the surface of each portland-cement specimen was lightly brushed with a whisk broom, to give a "sandpaper" texture. After curing for 7 days, each specimen was tested for skid resistance in this condition, which is identified as the "prior to polishing" condition. Subjecting a portland-cement concrete specimen to the entire wear and polish procedure used for bituminous

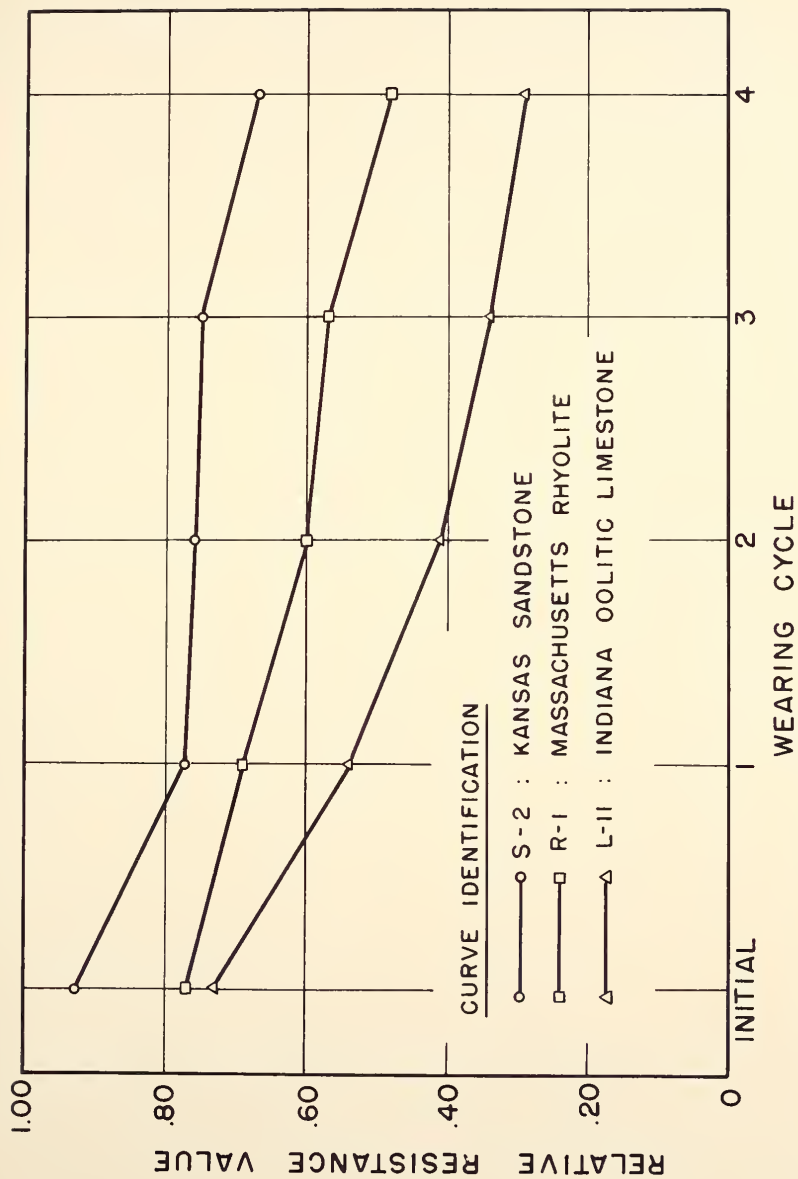


FIG. 2 VARIATION IN SKID RESISTANCE OF BITUMINOUS MIXTURES WITH WEAR

TABLE 1

Aggregate Gradation for Standard Laboratory Specimens

Passing Sieve	Retained on Sieve	Asphaltic Concrete	Portland-Cement Concrete
1/2 in	3/8 in	12	25
3/8 in	No. 4	26	25
No. 4	No. 6	0	0
No. 6	No. 16	1	12
No. 16	No. 30	12	12
No. 30	No. 60	11	10
No. 60	No. 100	3	6
No. 100	No. 200	2	0
No. 200	Pan	3	0
		100	100

mixtures, only resulted in a slight amount of wear of the mortar, and failed to expose an appreciable quantity of coarse aggregate. Concrete specimens which were subjected to a wearing procedure similar to, but slightly more severe than, that given to the bituminous mixtures are described as being in the "motor polished" condition. Each specimen was tested in the skid-test apparatus in this condition,

Next, the top 1/4 inch of each portland-cement specimen was removed by a masonry saw equipped with a diamond blade, and the freshly-sawed face was subjected to the same wearing procedure that had been given initially to the mortar surface. The specimen was again tested for skid resistance, this time in what is described as the "aggregate polished" condition. Figure 3 indicates the variation in skid resistance of three typical portland-cement specimens, with RRV's listed for each of the three points in wearing procedure. The specimens, upon which the results illustrated in Figure 3 were based, were composed of the same three aggregates used in the bituminous mixtures on which the RRV's plotted in Figure 2 were obtained.

SUMMARY OF THE INITIAL PHASES OF THE RESEARCH

A brief summary is presented of the results from the initial phases of the research on skid resistance at Purdue University. These data are given since this information is closely related to the blending study which follows, and the recommendations submitted in the final section for minimizing pavement slipperiness also refer to the findings of the early program of research. A complete treatment of this initial work is given in reference (7).

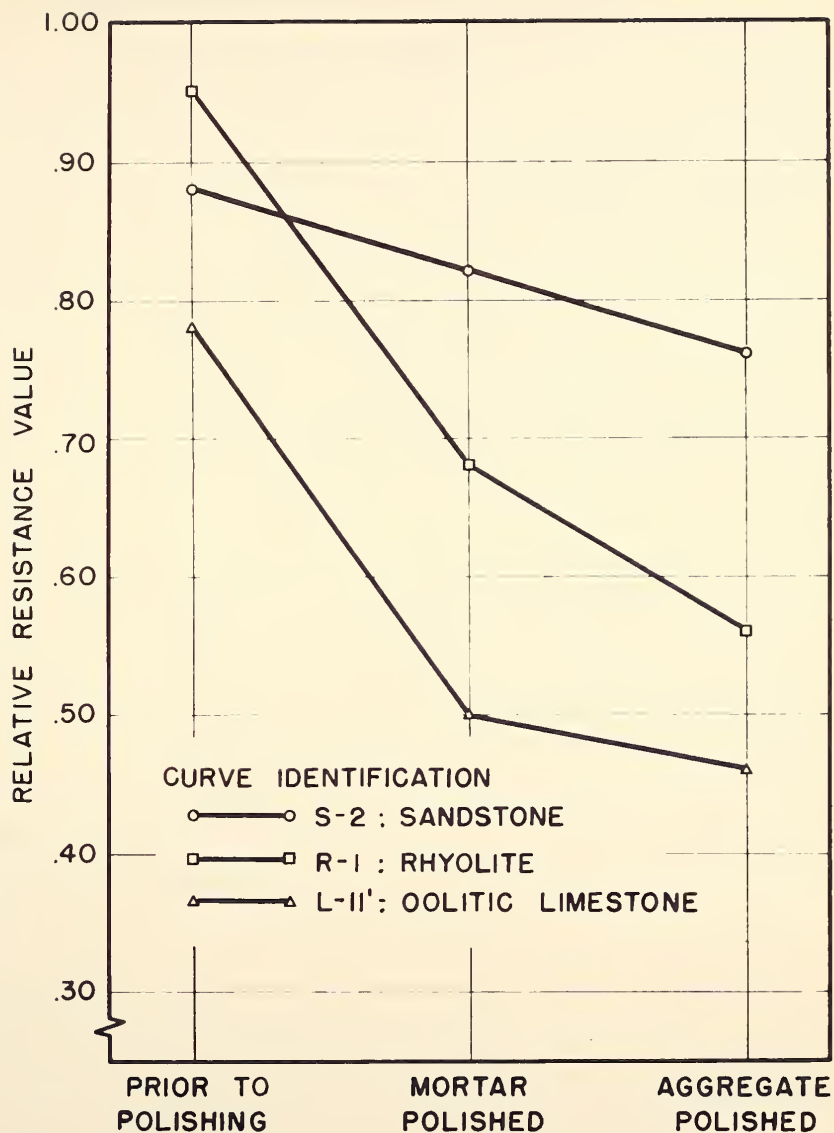


FIG. 3 POLISHING CHARACTERISTICS OF PORTLAND CEMENT CONCRETE

Polishing Characteristics of Mineral Aggregates

The results of the resistance to polishing of bituminous-concrete mixtures composed of 22 different aggregates are summarized in Figure 4. Relative resistance values at the completion of the fine-polish cycle are plotted as the ordinate with the type of aggregate used in each of the mixtures indicated along the abscissa. Twelve limestones (L-1 through L-12) were included in the study, and the values obtained for these aggregates are plotted to the left of Figure 4. Results for the other ten aggregates which, reading from left to right, include a chert, a rhyolite, two high-quartz gravels, two sandstones, two diabases, a granite, and a slag, are plotted to the right in Figure 4.

An examination of these results leads to three conclusions with regard to bituminous-concrete mixtures, which apply primarily to the aggregate types included in this study:

1. Limestones, as a group, do not exhibit as good resistance to polishing as other aggregate types. The average RRV for mixes containing the 12 limestones was 0.45 while mixes composed of the other aggregates had an average RRV of 0.63.
2. There is appreciable variability in the resistance to polishing of the various limestones. Mixes in which the limestone consisted almost entirely of calcium carbonate polished quite readily and produced RRV's in the low 0.30's. Mixes containing highly-dolomitic limestones exhibited somewhat better resistance to polishing with RRV's in the middle 0.50's.
3. Sandstones possess by far the best resistance to polishing of any of the aggregates evaluated in this study.

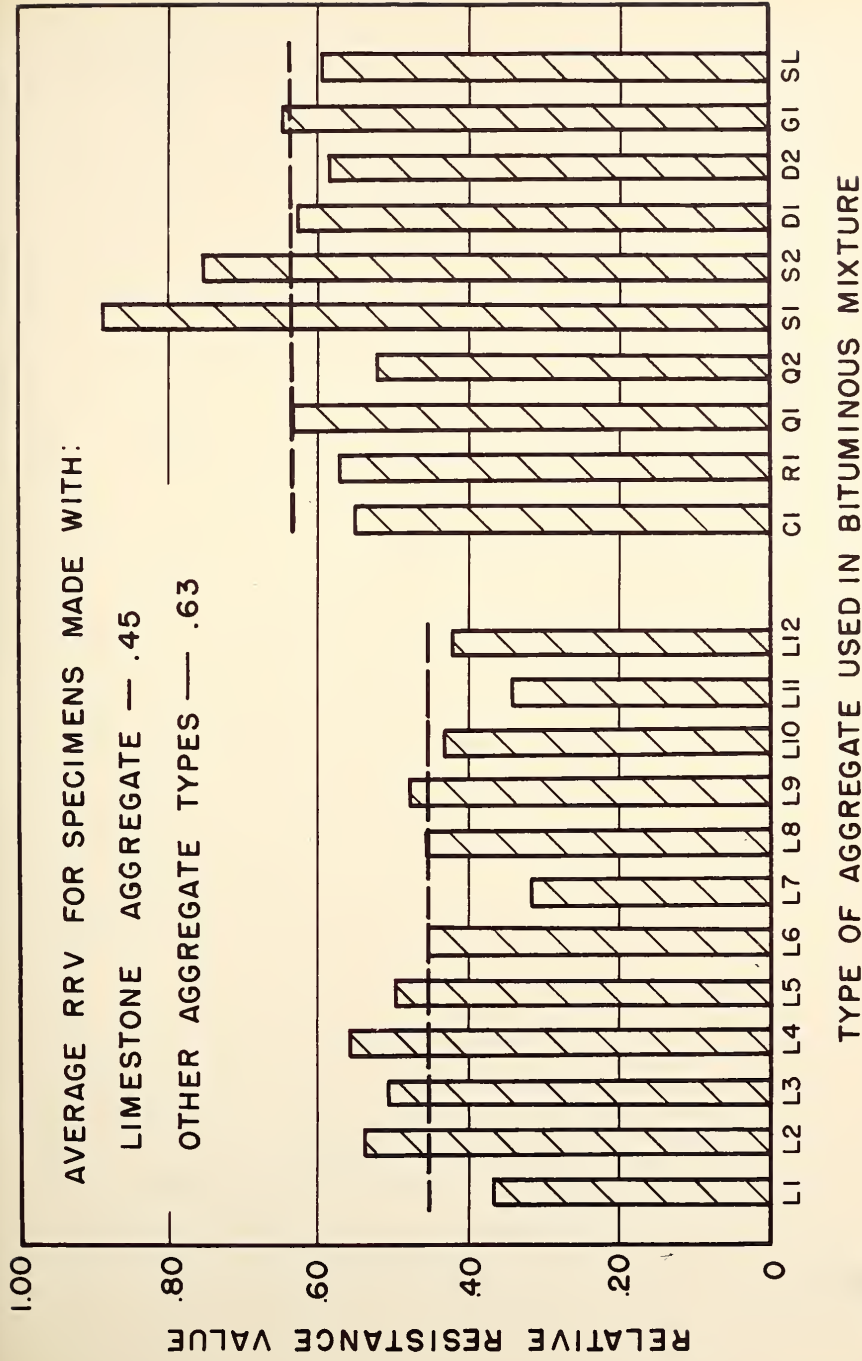


FIG. 4 SKIDDING RESISTANCE OF BITUMINOUS MIXTURES AT THE COMPLETION OF THE FINE POLISH CYCLE

In order to compare the polishing characteristics of aggregates in portland-cement and bituminous mixtures, six aggregates were selected for study. Portland-cement and bituminous specimens were made with each of the six aggregates, subjected to their respective wear and polish procedures, and evaluated for skid resistance in the laboratory testing equipment. The results of this study are summarized in Figure 1, and indicate that if appreciable exposure of the coarse aggregate occurs in specimens composed entirely of one aggregate type, the skid-resistance of portland-cement and bituminous mixtures will be similar.

Effect of Surface Texture and Initial Aggregate Shape

The bituminous mixtures for the aggregate-evaluation study were composed entirely of crushed aggregate conforming to a standard gradation. To investigate the effect of specimen surface texture, as determined primarily by gradation, and initial aggregate shape on the skid-resistance of bituminous mixtures, four representative aggregates were selected for additional study. Two of these aggregates were limestones; one, a highly dolomitic limestone (L-4) that had exhibited good resistance to polishing; and the other, an oolitic limestone (L-11) which had polished quite readily. The other two aggregates were a rhyolite (R-1) and a sandstone (S-2).

For the surface-texture investigation bituminous mixtures conforming to five different gradations were molded, subjected to the wear and polish procedure, and evaluated for skid resistance. Gradation No. 1 was very open-graded, with the mixtures becoming progressively more dense-graded as the gradation number increased. (Gradation No. 5 is listed in Table 2, and the other gradations are given in reference (7). Mixtures conforming to gradation No. 1 were so open-graded that

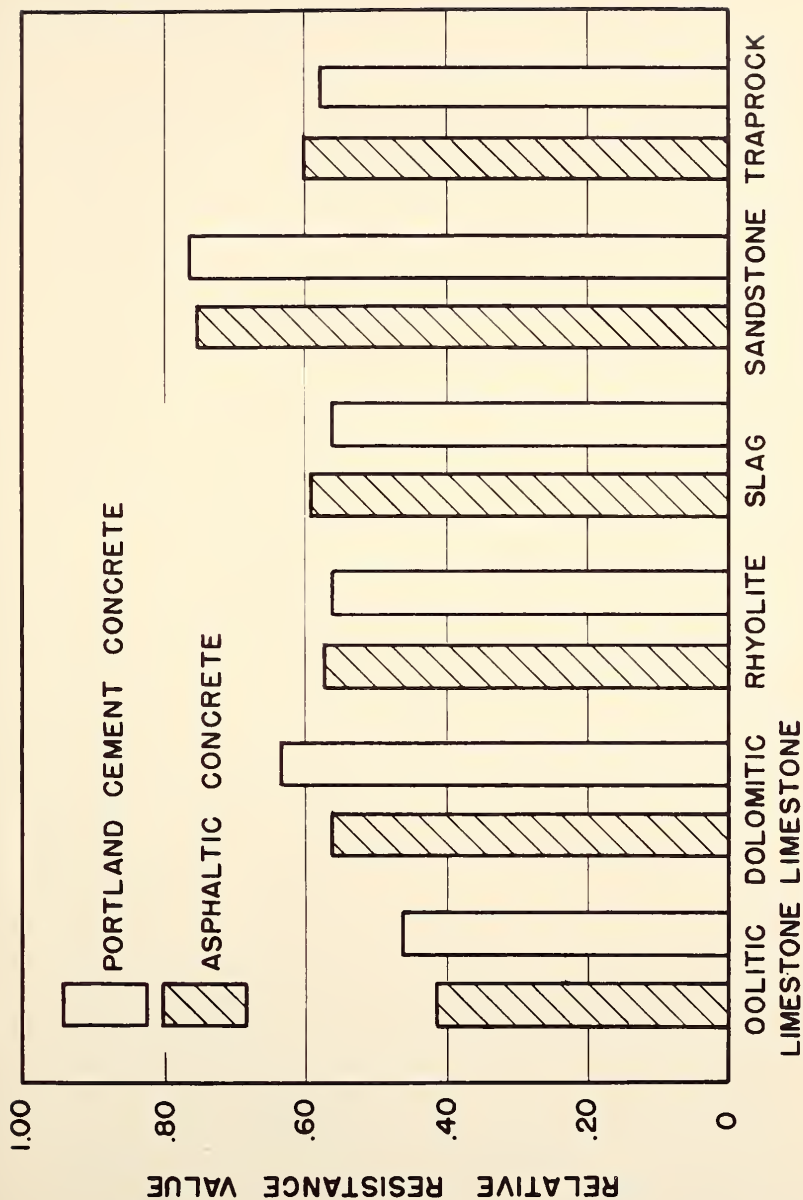


FIG. 5 SKID RESISTANCE OF PORTLAND CEMENT AND ASPHALTIC CONCRETE TEST SPECIMENS

they exhibited very little surface friability and resistance to the wearing procedure.

The two parts of the surface texture investigation are shown in Figure 6 by presenting relative losses of the gradations. Figure 6 shows the AEV's obtained with each of the four aggregates for the completion of the three high cycle wear test specimens confined to one gradation (No. 5). The most dense graded aggregate, and grade, was the most non-gradable in the high cycle wear test. The complete polish procedure, although the texture effect was not as great as the difference in aggregate types, in all cases causes the specimens exhibited better wear resistance than the corresponding open graded specimens.

To provide a basis for determining the effects of aggregate shape, a sample of each of the four selected aggregates was placed in a Los Angeles abrasion machine and revolved for four hours. In all balls were used. The wearing action of aggregate on aggregate and against the shell of the machine caused the individual pieces of aggregate to become quite rounded. The resulting material was then screened, weighed, and mixed in accordance with the standard procedure. The finished specimen was identical to the corresponding standard bituminous concrete specimen used in the aggregate evaluation study, except that the coarse and specimen contained aggregate would now be freshly crushed and the modified specimen consisted entirely of a artificially-rounded aggregate.

The relative resistance curves following initial polishing, coarse polish, and fine polish are plotted in Figure 7 for each type of specimens and for each of the four aggregates. The initial did not

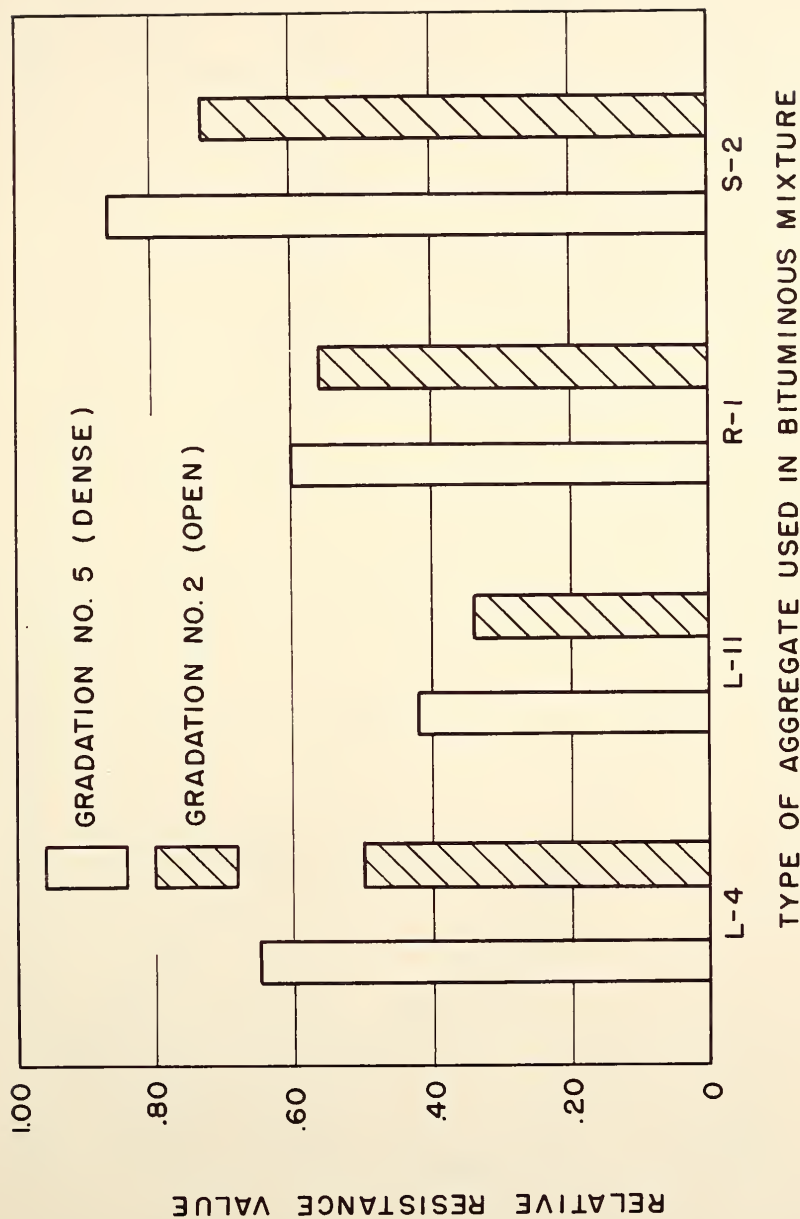


FIG. 6 COMPARISON OF THE RESISTANCE TO POLISHING OF
DENSE AND OPEN GRADED BITUMINOUS MIXTURES

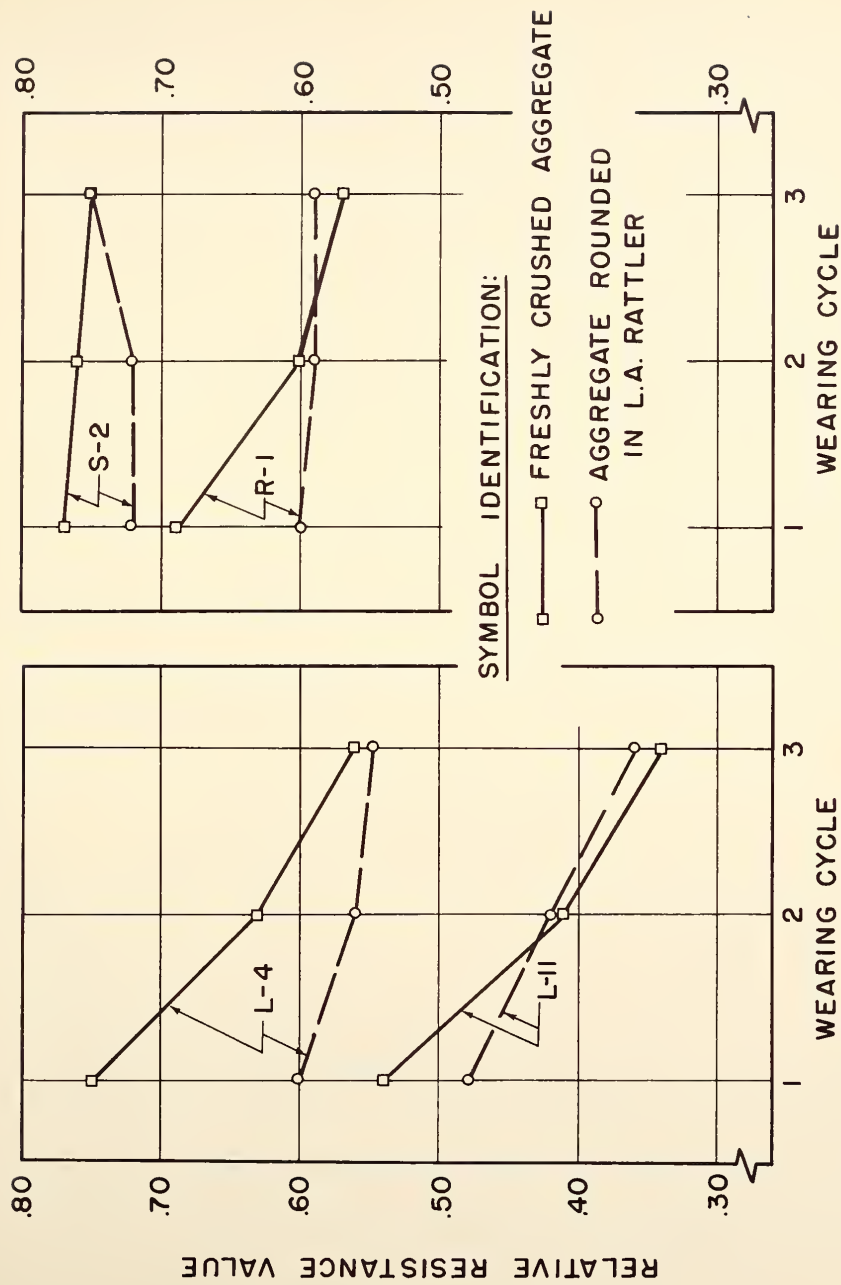


FIG. 7 EFFECT OF AGGREGATE SHAPE ON THE POLISHING CHARACTERISTICS OF BITUMINOUS MIXTURES

sistances of the specimens containing the angular aggregates were appreciably higher than for the corresponding rounded-aggregate specimens, which was to be expected. At the completion of the fine-polish cycle, however, for a given aggregate there was no significant difference between the skid resistances of the angular- and rounded-aggregate specimens.

THE SKID RESISTANCE OF SELECTED FINE-TEXTURED SURFACES

The term "fine-textured" is used in this section to describe the degree of openness of surfaces and is dependent upon the magnitude of the individual surface voids. The most dense-graded bituminous mixtures used in the surface-texture study, as well as the fine-grained, open-graded Kentucky rock asphalt and silica-sand surface treatments, all result in surfaces in which the size of each of the individual voids is small. These surfaces are identified as "fine-textured." By contrast, a "coarse-textured" surface is typified by a bituminous surface treatment consisting of one-size coarse aggregate in which the size of each surface void is large.

Initial Laboratory Investigation

The investigation of the effect of surface texture on the skid resistance of bituminous mixtures led to the conclusion that reasonably dense-graded mixes possess greater skid resistance than open-graded mixes of similar materials. Similarly, results of field studies (1, 2) indicate that fine-grained surfaces, containing hard angular particles, exhibit excellent resistance to skidding. In order to investigate this relationship more fully, and also in order to study various materials as potential blending ingredients for improving the anti-

skid characteristics of polish-susceptible aggregates, 12 different fine-textured specimens were made and tested in the laboratory equipment.

The composition of the various mixtures is listed in Table 2. Three of the specimens were individually graded, but nine of the specimens conformed to gradation No. 5, the most dense-graded mixture of those used for the surface-texture investigation. In addition to the four aggregates used in the surface-texture and initial-shape studies, i. e. oolitic and dolomitic limestone, rhyolite, and sandstone, two slags and three natural sands were included. SL-1 was a typical gray blast-furnace slag with a high degree of porosity, while SL-2 was a black, glassy non-porous slag.

The particle shapes of the three natural sands are shown in the left column of Figure 8. These enlarged photographs were made of material passing the No. 30 and retained on the No. 50 sieve. The Elkhart sand, appearing at the top of the column, is the most rounded of the three; the Lafayette sand is somewhat more angular than the Elkhart sand; and the Virginia sand is harsher than the Lafayette sand.

The other three materials shown in Figure 8 also were used in making fine-textured specimens. The very harsh silica sand, illustrated by the top figure in the right-hand column, was obtained from Virginia. The silica-sand mixture listed in Table 2 is representative of a type of non-skid treatment which has been used very successfully in that State.

The enlarged photograph of particles contained in Kentucky rock asphalt was made after the asphalt has been extracted from the specimen. These hard quartz particles are somewhat less angular than the grains of the Virginia silica sand.

TABLE 2
Mixture Composition of Fine-Textured Specimens

Passing Sieve	Retained Sieve	Gradation No. 5	Silica Sand	Carbor- undum	Kentucky Rock Asphalt
No. 4	No. 8	19.2	0	0	0
No. 8	No. 16	15.1	0	0	1.7
No. 16	No. 30	14.0	0.5	38.1	4.3
No. 30	No. 50	13.3	38.4	11.7	43.3
No. 50	No. 100	15.1	56.7	0.1	37.2
No. 100	No. 200	13.7	4.0	0.1	6.8
No. 200	Pan	<u>9.6</u>	<u>0.4</u>	<u>0</u>	<u>6.7</u>
		100.0	100.0	100.0	100.0

Gradation No. 5 Specimen:

L-4, L-11, and SI-1 ----- 5.7 percent asphalt

All other aggregates ----- 5.4 percent asphalt

Silica Sand Specimen:

1700 g. of silica sand; 40 g. hydrated lime; and
6.2 percent asphalt.

Carborundum Specimen:

900 g. of silica sand; 900 g. carborundum;
40 g. hydrated lime; and 5.7 percent asphalt.

Kentucky Rock Asphalt Specimen:

1800 g. of the total natural material, of which
8.03 percent was asphalt, as determined by extraction.



ELKHART SAND



SILICA SAND



LAFAYETTE SAND



KENTUCKY ROCK ASPHALT



VIRGINIA SAND



CARBORUNDUM

FIG. 8 PARTICLE SHAPE OF MATERIALS USED FOR DENSE-TEXTURED SPECIMENS

The remaining print in Figure 8 is of a sample of carborundum. While it may not be practical to use this material as a highway aggregate, it was felt that a comparison of an artificial abrasive with some of the common highway aggregates would be of interest. The degree of harshness of carborundum approaches that of the Virginia silica sand. In selecting a suitable mixture for a fine-textured specimen, carborundum and silica sand were combined in equal parts by weight, as indicated in Table 2.

Two other specimens included in the fine-textured category were a surface which consisted entirely of 85-100 penetration asphalt cement and a specimen of solid ice. The asphalt-cement specimen was tested in the wet condition only, and the ice in both the dry and wet conditions. These surfaces were included to indicate the relative resistance values for the most slippery conditions likely to be encountered on a highway surface.

In the initial investigation of fine-textured surfaces, fourteen specimens were tested in the laboratory skid-test apparatus in the conventional manner. The relative resistance values of the nine dense-graded bituminous mixtures at the completion of the total wear and polish procedure are shown to the left of Figure 9. Results for the three non-skid specimens are plotted adjacent to them, and for the three slippery specimens at the right of the figure.

The four aggregates which had been included in the aggregate-evaluation study using an open-graded mixture, i.e. oolitic and dolomitic limestone, rhyolite, and sandstone, indicated about the same relative degree of effectiveness in developing skid resistance that was found in the previous study. Bituminous mixtures containing dolomitic limestone

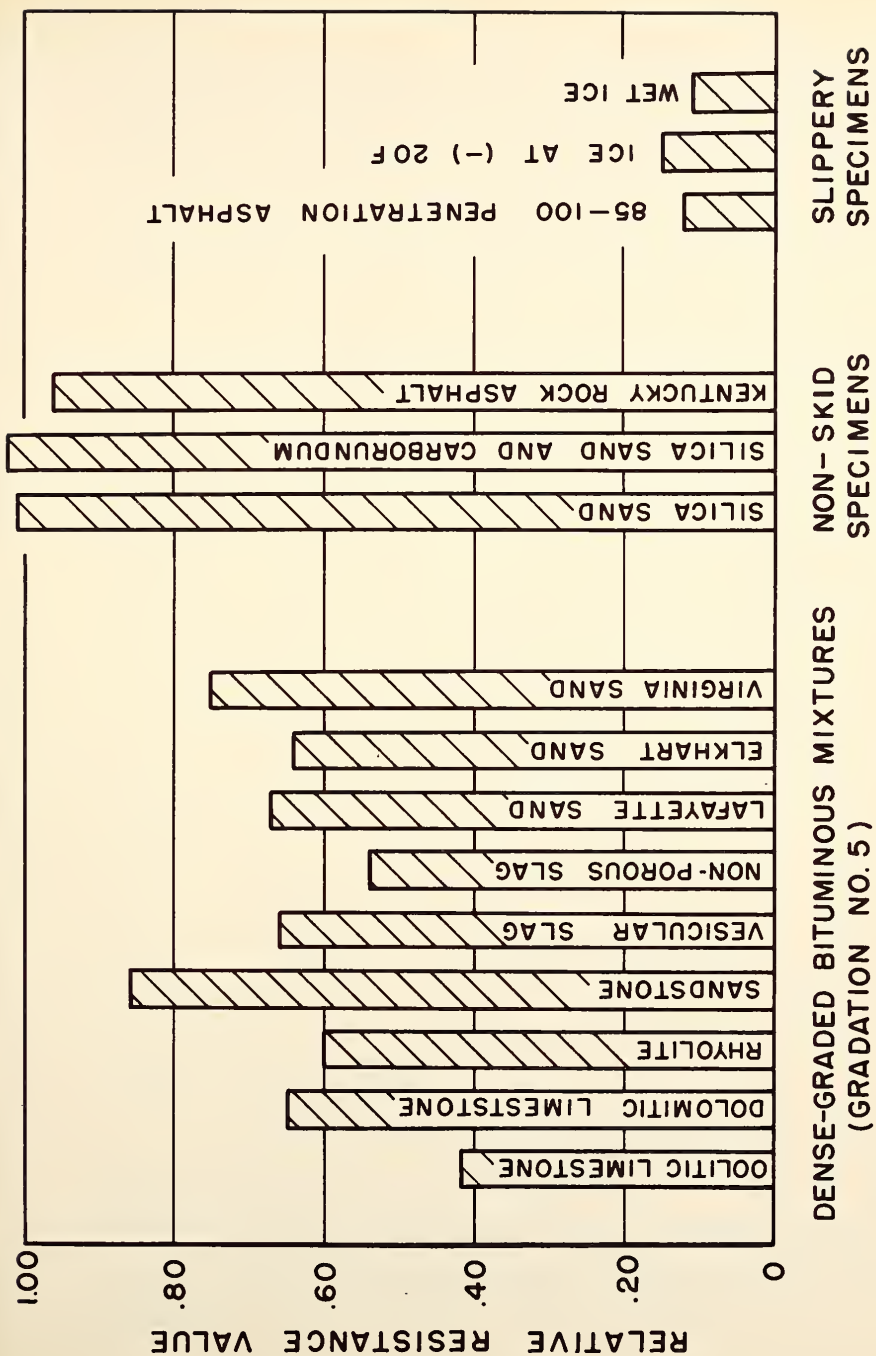


FIG. 9 THE SKIDDING RESISTANCE OF SELECTED FINE-TEXTURED SPECIMENS

and rhyolite exhibited appreciably better skidding resistance than those made with oolitic limestone, while sandstone bituminous mixtures gave by far the best anti-skid characteristics. The vesicular slag gave results, which were comparable to those of the dolomitic limestones, and appreciably higher than for the non-porous slag.

The three graded natural sands all exhibited good anti-skid characteristics. Bituminous mixtures containing Elkhart, Lafayette, and Virginia sand gave relative resistance values of 0.64, 0.67, and 0.75, respectively. As indicated by Figure 8, and mentioned previously, the Elkhart sand was the most rounded and the Virginia sand the most angular of the three. Consequently, it would appear that the skidding resistance of the fine-textured bituminous mixtures is dependent to some degree on the angularity of the aggregate particles.

The three "non-skid" surface types all exhibited excellent anti-skid characteristics. The laboratory Kentucky rock asphalt specimen had an RRV of 0.96, which was slightly less than the value obtained on a Kentucky rock asphalt specimen core from the pavement surface. This was probably due to the fact that the texture of the laboratory specimen was more uniform than that of the field specimen, in which some of the particles were dislodged from the surface, resulting in a slightly roughened texture.

The silica-sand and the combination silica-sand and carborundum specimens gave essentially equal results. They both exhibited somewhat better anti-skid properties than the laboratory Kentucky rock asphalt specimen, probably due to greater angularity of the individual particles.

Values for the three slippery sections were plotted to provide a better appreciation of the significance of a low RRV. Wet ice, with an RRV of 0.11, was the most slippery of any of the specimens tested, while a wet pure asphalt surface was only slightly higher at 0.12.

Indiana Natural Sands

The excellent skid resistance exhibited by some of the fine-textured surfaces encouraged a more thorough investigation of the characteristics of the sands available in Indiana as possible sources for a relatively inexpensive non-skid surface treatment. Twenty natural sands, conforming to Indiana Specifications for No. 14 sand (9), were obtained from commercial sources distributed throughout the State. Sieve analysis on these sands indicated that essentially all of the material passed the No. 4 sieve, the majority of the sand was fairly well-graded between the No. 8 and No. 50 sieves, and from 1 to 4 percent of the material passed the No. 100 sieve.

Two sources of sand with a high silica content were included in the study, as well as one dune sand. The majority of the particles for the silica sands were in the No. 30 to No. 50 range, while the dune sand was somewhat finer.

Laboratory specimens were formed with each of these materials as received. An asphalt content of 6 percent, based on the total weight of the mixture, was used with the No. 14 sands; 6.5 percent with the silica sands; and 7 percent with the dune sand. Relative resistance values corresponding to three points in the wear and polish procedure are listed in Table 3 for mixtures made from each of the 23 sands.

The 20 sands from commercial sources exhibited fairly uniform skid resistances which, although not as high as for some of the non-skid surface treatments previously discussed, indicated that the use of these sands could produce surfaces possessing reasonably good anti-skid

TABLE 3

Skid Resistance of Indiana Sands

		<u>Relative Resistance Value</u>		
A.	Indiana Specifications No. 14 Sand - 6% asphalt	After Initial Rolling	After Coarse Wear	After Fine Polish
	1.	.59	.72	.70
	2.	.66	.70	.63
	3.	.64	.72	.64
	4.	.65	.73	.63
	5.	.63	.67	.67
	6.	.60	.66	.68
	7.	.60	.65	.66
	8.	.60	.64	.64
	9.	.54	.66	.61
	10.	.65	.67	.65
	11.	.56	.65	.60
	12.	.66	.70	.65
	13.	.65	.70	.63
	14.	.62	.65	.65
	15.	.52	.64	.57
	16.	.66	.68	.62
	17.	.60	.70	.62
	18.	.73	.70	.68
	19.	.70	.71	.68
	20.	.55	.67	.66
B.	Indiana High - Silica Sand - 6.5% asphalt			
	1.	.85	.78	.98
	2.	.64	.70	.69
C.	Indiana Dune Sand - 7% asphalt			
	1.	.80	Surface failed during testing.	

characteristics. After initial rolling the 20 sands gave an average RRV of 0.62, with a range in values from 0.52 to 0.73. Following the coarse-polish cycle, during which the asphalt was scoured from the surface aggregate and some of the larger naturally-rounded particles may have been roughened somewhat, the average RRV increased to 0.68, with a range from 0.64 to 0.72. The fine-polish cycle caused a decrease in skid resistance for most of the sands so that the final average RRV was 0.64, with a range from 0.57 to 0.70.

One of the silica sands exhibited excellent skid resistance and gave results comparable to that of the Virginia silica sand. The second silica sand, although of similar gradation, contained particles which were not as harsh as the first aggregate. In addition there appeared to be a dusty coating on the larger particles, and the skid resistance measurements with this sand were appreciably lower than with the harsh silica sand. The specimen made with dune sand exhibited good initial skid resistance, but did not possess sufficient durability to resist disintegration during the wearing and testing procedure.

Proprietary Mixes

To round out the picture on fine-textured surfaces, some of the proprietary mixes, which are currently being advocated as non-skid treatments, were investigated. One such mixture was a crushed diabase traprock to which had been added a powdered asphalt and an asphalt flux oil. The anti-skid characteristics of this treatment were good, but the initial stability of the mixture was low so that a specimen made of this material had to be cured some little time before testing in the laboratory apparatus.

Laboratory skid tests were also performed on resinous surface treatments containing emery, crushed quartz, and aluminum oxide. In forming these specimens the resin binder was placed on a prepared concrete disc in a liquid state and the grit was distributed over the surface. As the resin set chemically to form a tough plastic binder, the abrasive was rigidly held in place. Initially, resin specimens containing each of the three abrasives exhibited excellent skid resistances, with RRV's of over 1.00. After an appreciable amount of wear, however, the values decreased somewhat, with the quartz specimen showing a greater drop in skid resistance than the specimens containing the relatively harder abrasives. There is little particle-by-particle wear with surfaces of this nature, and the anti-skid characteristics are determined primarily by the initial shape and the resistance to polishing of the abrasive.

AGGREGATE BLENDING INVESTIGATION

In many areas of the United States the primary aggregate used in highway construction is limestone, and economic considerations, as well as the many desirable qualities of limestone for use in paving mixtures, require maximum utilization of this material. As illustrated by the aggregate-evaluation and field-correlation studies, some limestones polish quite readily when exposed to traffic. The purpose of the blending phase of the research was to investigate the effect of combining polish-resistant materials with a polish-susceptible limestone in an effort to obtain adequate skid resistance in the resulting paving mixture.

The limestone selected as the polish-susceptible aggregate was L-11, an oolitic limestone available in quantity, and one which had exhibited very little resistance to polishing. The aggregate was used for the entire study in both portland-cement and bituminous specimens.

the following table, which is a summary of the results.

The following table shows the results of the experiments. The first column gives the number of trials, the second column gives the number of correct responses, the third column gives the number of incorrect responses, the fourth column gives the number of correct responses as a percentage of the total number of trials, and the fifth column gives the number of incorrect responses as a percentage of the total number of trials. The results show that the number of correct responses increases with the number of trials, and that the number of incorrect responses decreases with the number of trials. The percentage of correct responses increases with the number of trials, and the percentage of incorrect responses decreases with the number of trials.

The following table shows the results of the experiments. The first column gives the number of trials, the second column gives the number of correct responses, the third column gives the number of incorrect responses, the fourth column gives the number of correct responses as a percentage of the total number of trials, and the fifth column gives the number of incorrect responses as a percentage of the total number of trials. The results show that the number of correct responses increases with the number of trials, and that the number of incorrect responses decreases with the number of trials. The percentage of correct responses increases with the number of trials, and the percentage of incorrect responses decreases with the number of trials.

Asphaltic Concrete

The blending materials included in the bituminous study were calcareous sandstone (S-2), vesicular slag (SL-1), non-porous slag (SL-2), Lafayette sand, silica sand, and carborundum. Blending of both fine and coarse aggregate was accomplished, for the most part, without deviating from the gradation of the standard specimen used in the aggregate-evaluation study. A portion of the oolitic limestone was replaced by an equal amount of the blending ingredient, with the gradation of the substitute and replaced materials being identical. With silica sand and carborundum, which were essentially one-size materials, it was not feasible to maintain the exact gradation of the standard specimen, and the blended mixture contained a higher percentage of fine material than the standard specimen.

Coarse-Aggregate Substitution. The two coarse aggregates which were studied as replacement materials were the sandstone (S-2) and the vesicular slag (SL-1). The fraction of the limestone on which the substitution was made was that portion retained on a No. 5 sieve. This constituted 48 per cent of the total aggregate. The amount of replacement material for each of five mixes was as follows:

Mixture Identification:	1	2	3	4	5
Per cent Substitution Based on Coarse Aggregate:	0	25	50	75	100
Per cent Substitution Based on Total Aggregate:	0	12	24	36	48

Since 48 per cent of the total mix was coarse aggregate, 100 per cent replacement of the coarse aggregate corresponded to 48 per cent of the total aggregate.

The specimens were subjected to the conventional testing and polishing procedure, and the results are shown graphically in Figure 10.

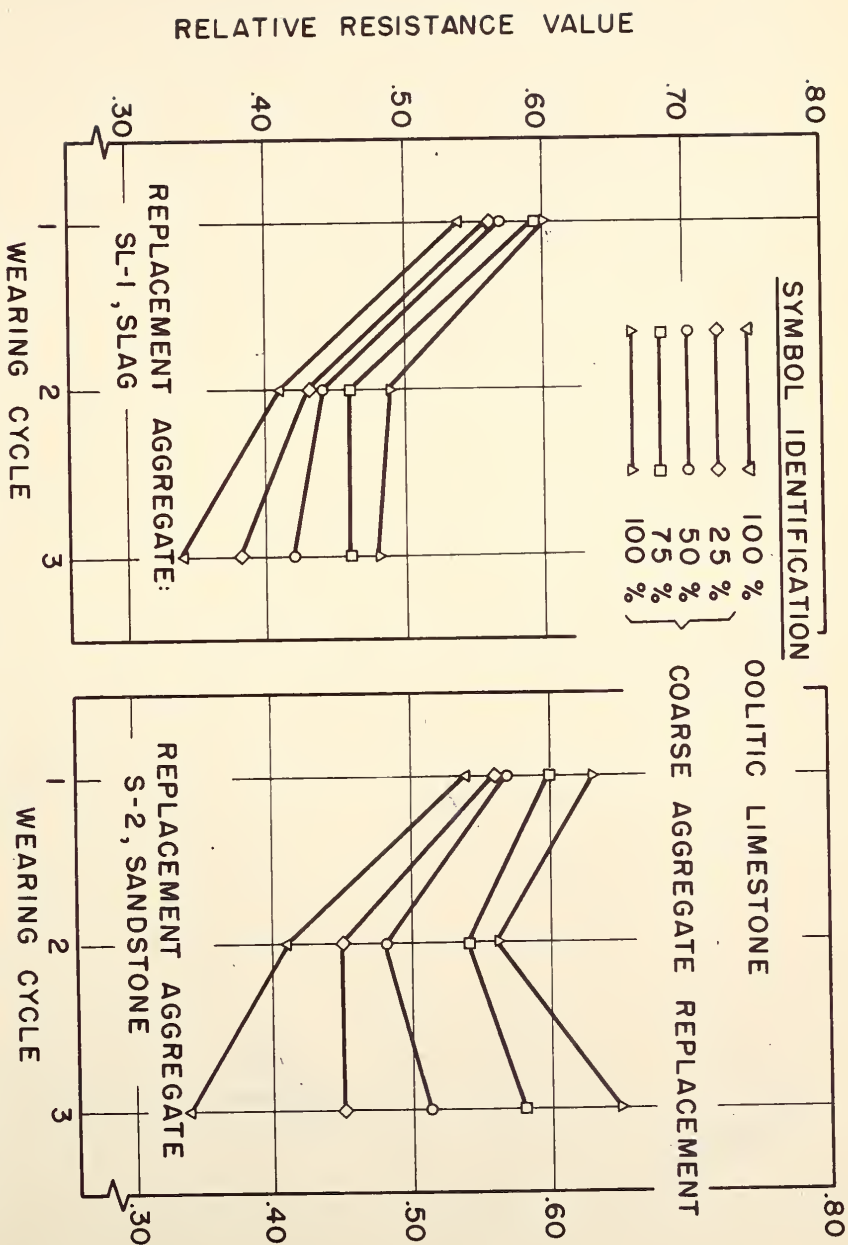


FIG. 10 EFFECT OF REPLACING THE COARSE AGGREGATE FRACTION WITH A POLISH RESISTANT MATERIAL

The five curves drawn for each type of replacement material represent the results for a bituminous mixture in which the aggregate consisted entirely of oolitic limestone, and for mixtures containing, respectively, 25, 50, 75, and 100 per cent coarse-aggregate replacement.

For the initial testing cycle, replacing a part of the coarse-aggregate fraction resulted in a slight improvement in skidding resistance, with the degree of effectiveness increasing with the per cent of substitution. This advantage became more significant as wear and polish progressed. The sandstone was much more effective in improving the anti-skid characteristics of the mixtures than the slag. As evaluated at the completion of the fine-polish cycle, a 50 per cent substitution of the coarse limestone with sandstone accomplished a greater increase in skid resistance than a 100 per cent coarse slag replacement.

An interesting aspect of the sandstone-replacement specimens was the fact that their skid resistance actually improved during the fine-polish cycle. Although there was an appreciable decrease in the skidding resistance of the specimens during the coarse-wear procedure, in which the angularity of the aggregate was reduced, subsequent polishing served to wear and erode away the softer limestone and asphalt matrix, and provided greater exposure of the skid-resistant sandstone. The specimen, in which the limestone coarse aggregate was entirely replaced by sandstone, exhibited better skid resistance at the completion of the fine-polish cycle than it had shown initially.

Fine-Aggregate Substitution. The specimens for evaluating fine-aggregate substitution also conformed to the standard laboratory specimen in gradation and asphalt content. The fraction of the material replaced was that passing the No. 4 sieve and retained on the No. 100 sieve. Forty-seven per cent of the total aggregate fell within this range. The amount

of replacement material for each of the five mixes was as follows:

Mixture Identification:	1	2	3	4	5
Per cent Substitution Based on Fine Aggregate:	0	25	50	75	100
Per cent Substitution Based on Fine Aggregate:	0	11.6	23.5	35.3	47.0

Four fine-aggregate replacement materials were investigated.

In addition to the vesicular slag and calcareous sandstone, used in the coarse-aggregate substitution study, a glassy non-porous slag (SL-2) and a natural sand from Lafayette, Indiana, also were included.

The test specimens were subjected to the conventional testing and polishing procedure, and the results are shown graphically in Figures 11 (a) and 11 (b). As with the coarse-aggregate substitution, the lowest curve of the five represents the results for a bituminous mixture made entirely with colitic limestone with the other four curves representing mixtures which contain, respectively, 25, 50, 75, and 100 percent fine-aggregate replacement.

In comparing the effectiveness of the four different replacement materials at the beginning of the wearing cycle, it is noted that both of the slags provided an appreciable improvement in the skidding resistance; the sandstone was somewhat less effective; and the Lafayette sand caused no significant change from the F&V determined for the 100 percent limestone specimen. The Lafayette sand was more rounded than the crushed limestone that it replaced, so even though it was an appreciably harder material, the two effects compensated in the initial condition, and the skidding resistance was unaffected by the substitution.

After an appreciable amount of wear, as indicated by the results at the completion of the fine-polish cycle, the relative effectiveness of the four materials was different from that of the initial condition.

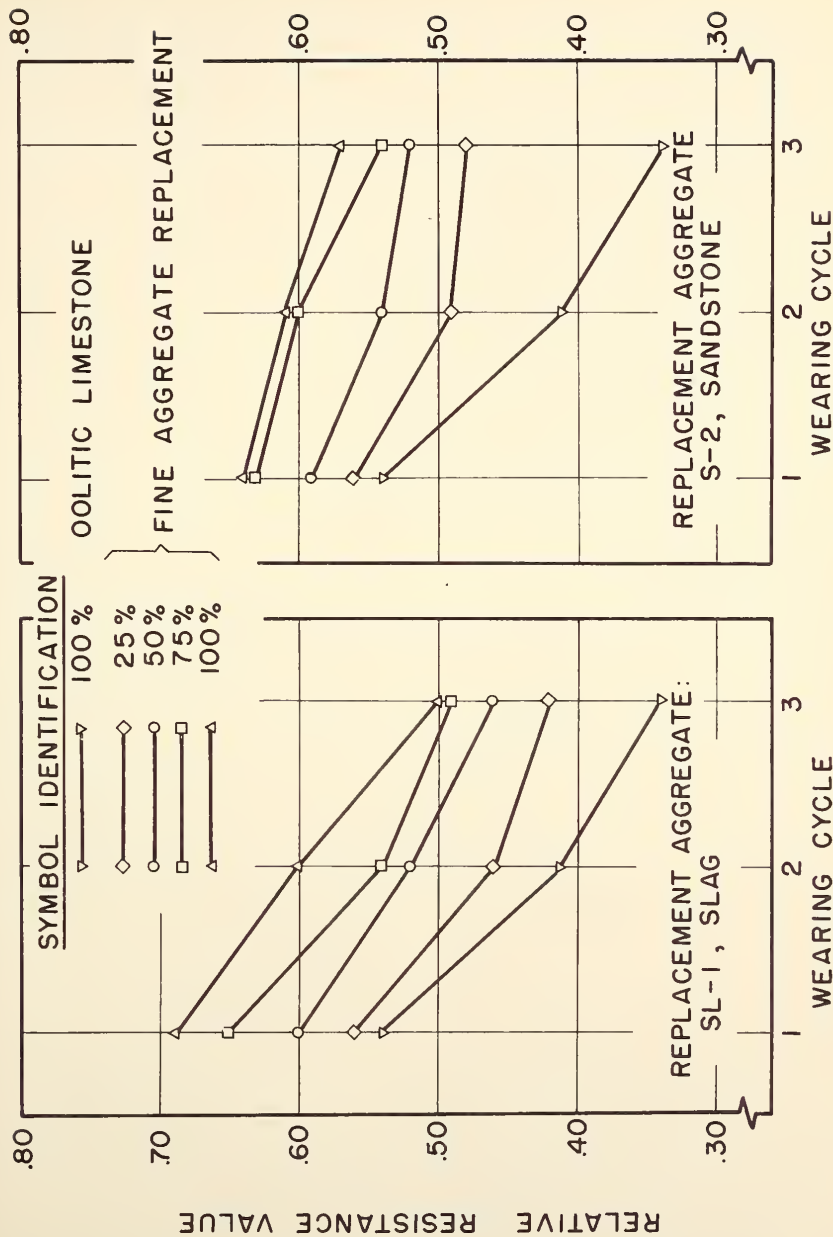


FIG. 11. EFFECT OF REPLACING THE FINE AGGREGATE FRACTION WITH A HARDER MATERIAL IN ASPHALTIC CONCRETE

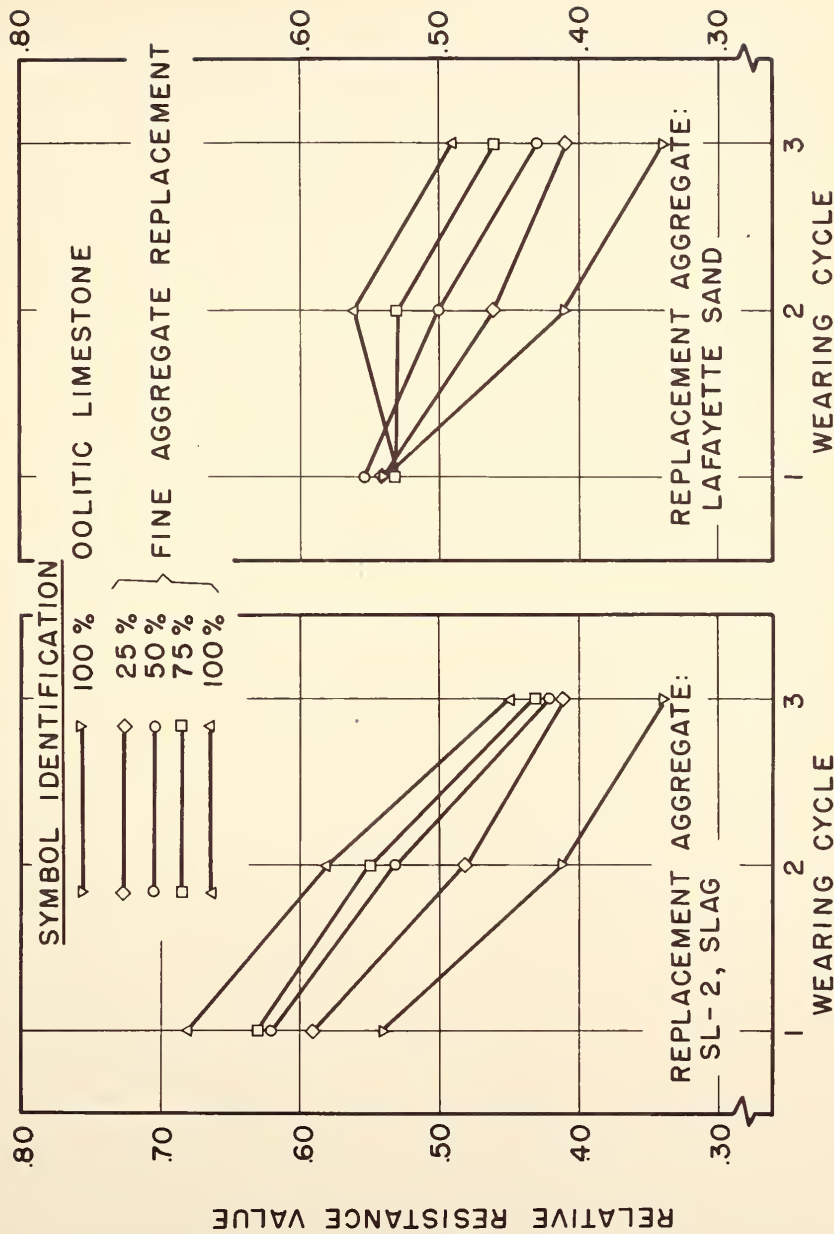


FIG. 11_b EFFECT OF REPLACING THE FINE AGGREGATE FRACTION WITH A HARDER MATERIAL IN ASPHALTIC CONCRETE

tion: the sandstone was the most effective, in terms of increasing the increase in the FWH factor, 0.34 to 0.57, and 15% polymer binder gave the maximum; the variation being not too great, however, in the range of 0.50 and 0.59, respectively, for 100 percent replacement of the replacement, and the non-polymer binder was the least effective of the four materials, with a total binder aggregate substitution of 0.45 and 0.45.

Fine Aggregates (Gothic Blending) The other two and the other two in this phase of the blending study were not sufficiently well-sorted to be used as substitute materials. However, in replacing a certain fraction of the calcitic limestone, as in the two related phases of this study, the blending material was obtained with a quantity of limestone which conformed to the standard gradation. This material was a very fine sand with a finer surface texture than that of the standard bituminous specimen, with the texture becoming increasingly finer as the percentage of combination was raised.

For the siliceous specimens, sufficient material was combined with the standard limestone to result in specimens with 10, 20, 30, and 40 percent of silica sand, respectively, based on the total weight of the aggregate. The other two and the other two were used, with the binder being 5, 10, 15, and 20 percent, respectively, also based on the total aggregate weight.

These specimens were subjected to the standard testing and wearing procedure, and the results are shown graphically in Figures 12. The combination of these non-siliceous materials with the calcitic limestone resulted in a significant increase in the anti-skid properties of the measures for all degrees of wear. There was probably a slight increase

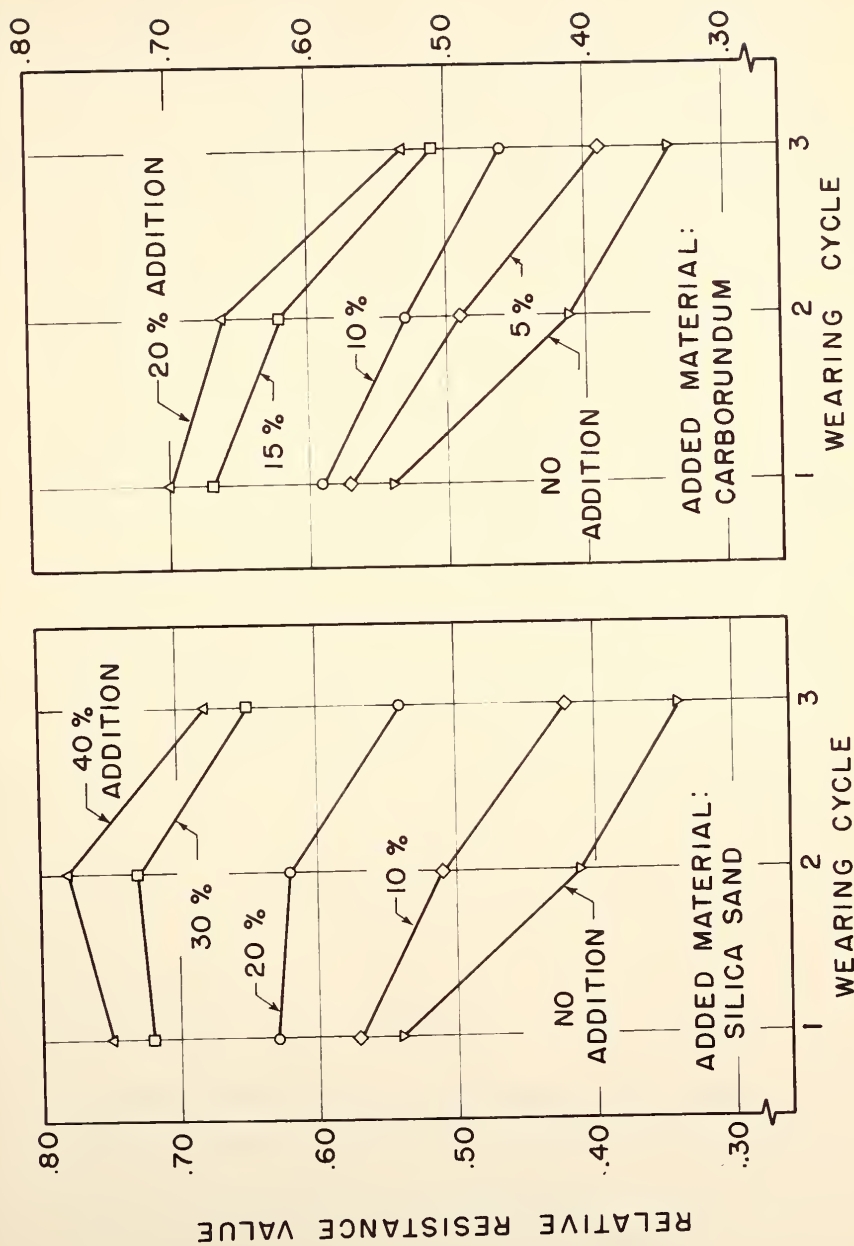


FIG. 12 EFFECT OF COMBINING A NON-SKID MATERIAL WITH A POLISH-SUSCEPTIBLE AGGREGATE IN ASPHALTIC CONCRETE

RELATIVE RESISTANCE VALUE

in skidding resistance due to the finer surface texture. Some of the improvement was attributable to the nature of the harsh, polish-resistant particles which were added.

A 20 percent addition of silica sand increased the RRV of the oolitic limestone specimen at the completion of the fine-polish cycle from 0.34 to 0.54, while a 40 percent addition doubled the RRV to 0.68. The addition of carborundum gave slightly higher anti-skid properties to the mixtures than did an equal percentage of silica sand in the early phases of the wearing procedure, but at the completion of the fine-polish cycle the difference was negligible.

Comparison of the Blending Treatments: A graphical comparison of the relative effectiveness of the various blending treatments is presented in Figure 13. This figure shows the relative resistance values at the completion of the fine-polish cycle, both for a specimen in which the aggregate consisted entirely of oolitic limestone and for specimens representing each of the blending treatments. Mixer selected for comparison contained the blending ingredient in a proportion of approximately one part to two parts of oolitic limestone. The coarse- and fine-aggregate substitution specimens had a higher amount of blending material, i.e., 36 and 25.3 percent, than the fine-aggregate combination specimens, which contained 30 percent silica sand and 20 percent carborundum, respectively.

Even though the percentage of blending material was slightly less than for the coarse- and fine-aggregate replacement treatments, combining silica sand with the oolitic limestone was the most effective method of improving the anti-skid characteristics of the test specimens. As previously indicated, the improved skidding resistance may have been due in part to the finer texture, resulting from the addition of a fine

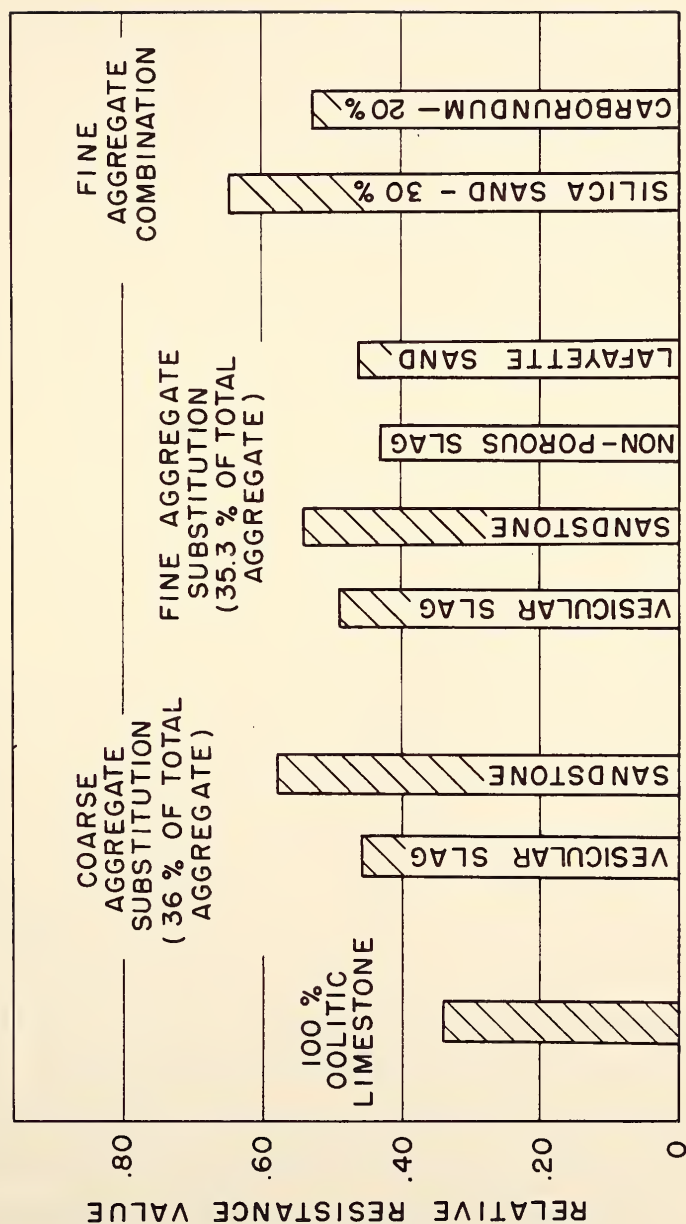


FIG. 13 THE EFFECT OF BLENDING VARIOUS MATERIALS
WITH A POLISH-SUSCEPTIBLE OOLITIC LIMESTONE
IN ASPHALTIC CONCRETE

material to the standard gradation, but was probably primarily dependent upon the harsh abrasive nature of the silica sand. In addition to the high resistance presented by the individual silica-sand particles, there also is evidence to indicate that the presence of the sand prevented the large limestone pieces from becoming too highly polished. One series of laboratory tests (7) indicated that grinding with coarse silica sand on a test specimen composed of limestone, after it had been polished to its most slippery condition using limestone mineral filler as an abrasive, improved the skid resistance of the polished surface.

The addition of carborundum had essentially the same effect as an equal amount of silica sand. Since it is a great deal more expensive than silica sand, the use of this material for the purpose of improving the skid resistance of paving mixtures is not discussed further.

The next most effective substitution material was S-2, the calcareous sandstone. As illustrated in Figure 13, in both the coarse- and fine-aggregate replacement specimens, the mixtures containing sandstone exhibited the highest skid resistance of all specimens included in the respective type of treatment. The vesicular slag showed somewhat better blending characteristics than the Lafayette sand, while the glassy, non-porous slag had the least effect of any of the materials in improving the anti-skid properties. A 75 per cent fine-aggregate replacement of the non-porous slag (SL-2) caused an increase in RRV of from 0.34 to only 0.43. Although the individual slag particles were hard and had sharp corners, they also possessed flat glassy faces which, under the kneading action of the rolling procedure, were oriented parallel to the surface and developed very little skid resistance during testing.

Portland Cement Concrete

The aggregate blending investigation with portland-cement concrete was much more limited in scope than for the bituminous study. Calcareous sandstone was used as a blending ingredient in both coarse-and fine-aggregate replacement; Lafayette sand also was used for fine-aggregate replacement; and silica sand was used in combination with the polish-susceptible limestone. Coarse-aggregate replacement was based upon the material retained on the No. 4 sieve, which constituted 50 per cent of the total aggregate, while fine-aggregate replacement was based upon the 50 per cent of the aggregate which passed the No. 4 sieve.

For the coarse-and fine-aggregate replacement studies, three mixtures, which conformed to a standard gradation, were used for each test series. For one specimen the aggregate consisted entirely of oolitic limestone; in the second, 50 per cent of either the coarse or fine aggregate was replaced with a blending material; and for the third, total substitution of either the coarse or fine fraction was made. Since the mixture was composed of equal parts of coarse and fine aggregate, a complete replacement of either of the fractions was equivalent to a 50 per cent substitution based on the total aggregate.

The results of the substitution studies with portland cement concrete are presented in Figures 14 and 15. Relative resistance values are plotted for each of the specimens on tests made initially, when the surface was in a lightly brushed "sandpaper" condition; after the motor-polished cycle; and after the surface was sawed and subjected to the aggregate-polished cycle.

A comparison of the effectiveness of crushed sandstone and natural sand as fine-aggregate replacement material is shown in Figure 14. Initially the sandstone caused an appreciable increase in the skid resistance of the blended specimen, while the rounded natural sand particles

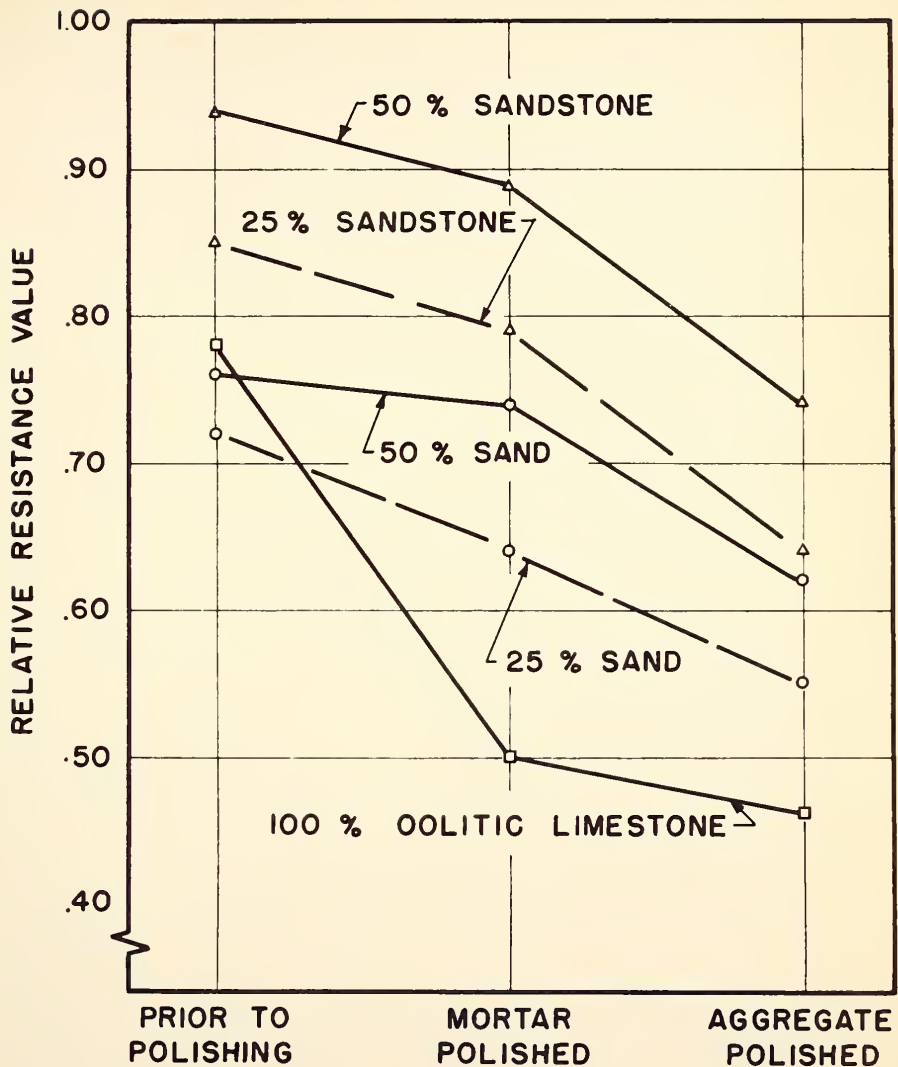


FIG.14 FINE AGGREGATE REPLACEMENT
IN PORTLAND CEMENT CONCRETE

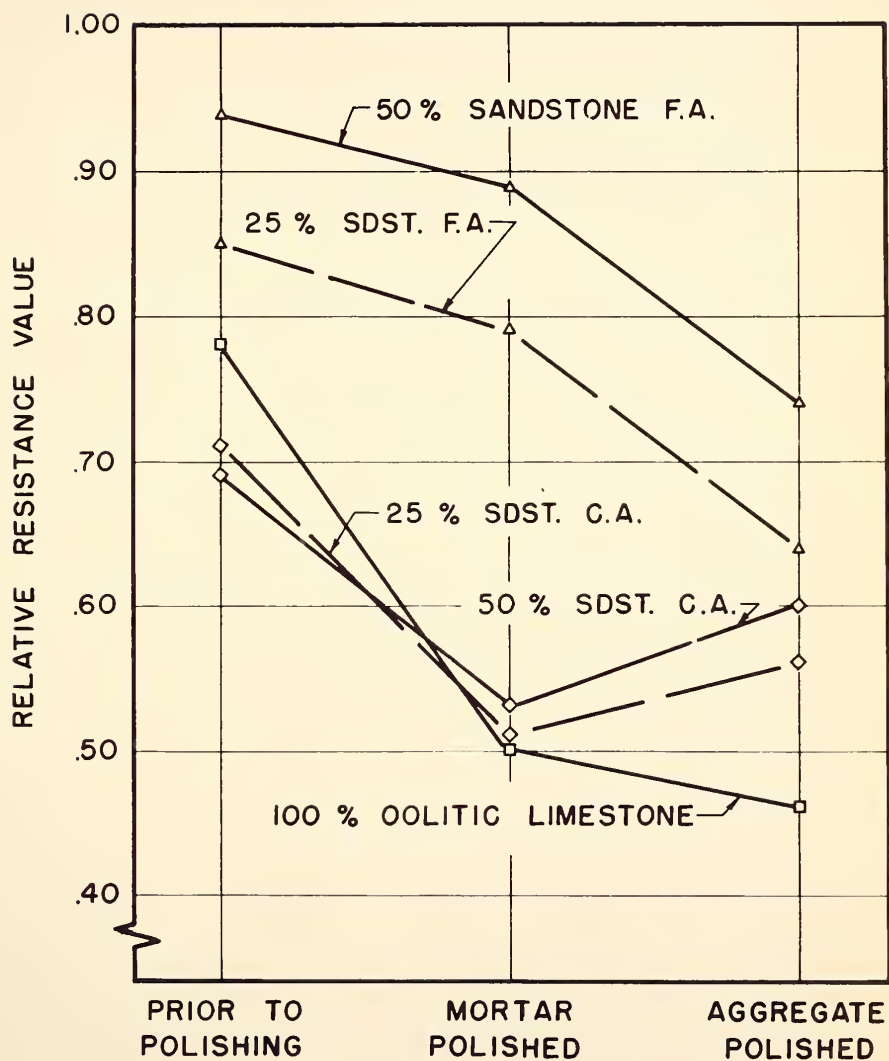


FIG. 15 BLENDING SANDSTONE WITH OOLITIC LIMESTONE IN P.C.C.

resulted in lower RRV's than were measured for the specimen made entirely of oolitic limestone. After some wear, the use of both materials provided an improvement in skid resistance, with the sandstone accomplishing by far a more significant increase. A 25 per cent replacement with sandstone, based on the total weight of the aggregate, was somewhat more effective in improving skid resistance than a 50 per cent natural-sand substitution.

Figure 15 illustrates the relative effectiveness of substituting an equal amount of coarse or fine sandstone in a concrete specimen containing a polish-susceptible aggregate. The addition of the sandstone coarse aggregate caused a decrease in the initial skid resistance of the blended specimen, as compared to the 100 per cent limestone specimen. After the mortar-polish cycle, in which very little of the coarse aggregate was exposed, the coarse sandstone caused a negligible increase in skid resistance, while an equal weight of fine sandstone caused a tremendous improvement in the anti-skid properties of the blended specimens.

Even after the top 1/4 inch of each specimen had been sawed off, resulting in maximum exposure of the coarse aggregate, fine-aggregate replacement with sandstone was much more effective in improving the skid resistance than was coarse-aggregate replacement. At the completion of the aggregate-polish cycle, a 25 per cent replacement with sandstone fine aggregate increased the RRV of a 100 per cent oolitic limestone specimen from 0.46 to 0.64, while a 50 per cent sandstone coarse-aggregate substitution resulted in an RRV of only 0.60.

The use of silica sand as a blending material in portland-cement concrete was investigated by combining a given amount of the sand with a quantity of limestone conforming to the standard gradation. This material was quite effective in improving the anti-skid properties of specimens

made from the limestone. A 20 per cent silica-sand combination, based on the total weight of the aggregate, effected almost the identical results that a 25 per cent fine sandstone replacement accomplished for all three points in the wearing cycle. Similarly, a 40 per cent silica-sand combination caused an increase in skid resistance approximately the same as that experienced with a 50 per cent fine-sandstone substitution. Since the results for the two blending materials were nearly identical, a plot of the variation in skid resistance due to the addition of silica sand is not included with this report.

RECOMMENDATIONS FOR MINIMIZING PAVEMENT SLIPPERINESS

A summary of the results of this investigation is presented in this section, along with suggestions as to design and construction practices which tend to minimize pavement slipperiness. Some of these recommendations are rather obvious, or currently are fairly well recognized, while others have been submitted previously in conjunction with the initial phase of this study (7); but all are included for the sake of completeness in summarizing the total findings of the research program to date. This was a laboratory investigation, restricted in scope to the materials and testing procedures previously enumerated, and the extension of this knowledge to predict the performance of pavement surfaces may not be completely objective. However, the following discussion is intended to be an unbiased evaluation of the program of research, and includes a very general application of the major findings of this study to highway construction practices which will lessen the occurrence of pavement surfaces which are "Slippery When Wet."

1. If an excess of asphalt does not occur at the surface, dense-graded bituminous mixtures will exhibit somewhat better anti-skid characteristics than open-graded mixtures composed of identical aggregate.

Dense-graded mixtures exhibit a greater tendency toward "bleeding," due to the additional compaction of traffic, than open-graded mixtures; but if this contingency is adequately considered in the design of the mixture, the dense-graded surfaces, by furnishing a greater uniformity of friction transfer over the entire contact area between the tire and surface, provide somewhat greater skid resistance than pavements containing surface voids of appreciable individual size. In addition, an open-graded surface exposes the aggregate to greater envelopment by the tire and to a higher polishing effort than a dense-graded surface.

2. Since surfaces containing crushed aggregate possess better initial skid-resistance than pavements made from rounded aggregates of the same composition, there is some justification, based on skid resistance alone, for requiring that any naturally-rounded coarse aggregate be entirely crushed if it is to be used in the pavement surface. After an appreciable period of wear, however, the skid resistance of the two surfaces will be nearly identical.

3. The polishing characteristics of aggregates will be similar both in portland-cement and in bituminous mixtures which are composed entirely of one aggregate type. However, it will usually require a greater wearing effort to polish the aggregate and to arrive at the ultimate slippery condition with portland-cement concrete as compared to bituminous surfaces.

4. There are certain limestones which should not constitute the total surface aggregate in bituminous pavements. Results of the initial laboratory study indicate that uniform fine-grained or oolitic limestones, consisting essentially of pure calcium carbonate, fall in this category. Surfaces of this nature possess only fair skid resistance when new, and may become dangerously slippery after a moderate amount of traffic.

5. Other types of limestones, such as the highly-dolomitic Indiana limestone, may be entirely satisfactory as the total surface aggregate for bituminous pavements if severe traffic conditions are not anticipated. Surfaces composed of these more-resistant limestones may ultimately polish; and, if traffic is extreme, can do so in a relatively short period. However, this same observation also can be made for pavements constructed with such aggregates as the fine-grained basalts, chert, and high-quartz gravel. These relatively polish-resistant aggregates may retain a certain degree of their initial angularity for an appreciable period, but due to the uniform nature of wear of the fine-grained structure, can ultimately polish excessively.

6. In order for a pavement surface, constructed either with portland cement or bituminous materials, to retain a non-skid surface under prolonged action of heavy traffic, some type of differential wear of the surface components is essential, since a uniformly-polished surface will be dangerously slippery when wet. For portland-cement concrete, this differential wear may occur due to the variation in resistance to wear of the cement paste and the fine and coarse aggregate. For both portland-cement and bituminous surfaces an aggregate, such as sandstone or some varieties of granite for which a coarse particle-by-particle type of wear occurs, may contribute to excellent skid resistance. Similarly the differential wear that takes place with Kentucky rock asphalt or a silica-sand surface treatment, due to ejection of aggregate particles from the pavement surface by traffic, results in a "non-skid" pavement.

7. Blending of a polish-resistant fine aggregate to improve the anti-skid characteristics of a polish-susceptible limestone is, at best, only moderately successful with bituminous mixtures. The laboratory investigation indicated that an appreciable quantity of a harsh

material, such as silica sand, was required to increase the skid resistance to a reasonable value. This quantity of silica sand probably could be used much more effectively as a non-skid surface treatment. Frequently the nature of wear of a bituminous highway surface is such that the fine-aggregate and asphalt matrix erodes away, and the area of contact between the tire and pavement consists almost entirely of coarse aggregate. For such a condition, the blending of skid-resistant fine material results in little improvement in the anti-skid characteristics of the mixture.

8. Blending of a polish-resistant fine aggregate to improve the anti-skid characteristics of a polish-susceptible limestone in portland-cement concrete is much more effective than with bituminous mixtures. The fine-aggregate mortar makes an important contribution to the skid resistance developed by portland-cement concrete, even after wear has progressed to the point where appreciable amounts of coarse aggregate are exposed. Laboratory results indicate that the use of a harsh, resistant fine aggregate with a polish-susceptible limestone coarse-aggregate will usually result in good skid resistance of the mixture, while even a naturally-rounded sand will promote sufficient differential wear to develop adequate skid resistance.

9. Limestone should not be used as the total aggregate in portland-cement concrete pavements. If the cement paste, the fine-aggregate of the mortar, and the coarse aggregate all possess essentially the same resistance to wear, a uniformly-polished surface may result that is dangerously slippery when wet.

10. From the skid-resistance standpoint, the majority of natural Indiana sands can be used in satisfactory bituminous surface

treatments, and this would probably be generally true on a national basis. There is some variability of results depending upon the roundness and degree of polish of the individual particles, and the resulting treatment may not be as skid resistant as those composed of harsh silica sand or crushed sandstone; but consideration should be directed toward natural sand deposits as potential sources of material capable of producing surfaces with adequate skid resistance.

11. A non-skid silica-sand surface treatment, such as that developed by Virginia (4), probably holds the best promise of being generally accepted as an effective means of combating pavement slipperiness. The continuous rejuvenation of the surface, which accompanies the particle-by-particle type of wear, results in excellent anti-skid characteristics during the entire life of the treatment. Such non-skid surface treatments, when placed on existing slippery pavements that are structurally adequate or used as a preventive measure in new construction with polish-susceptible aggregates, can make a significant contribution to driving safety.

ACKNOWLEDGMENTS

The authors acknowledge the complete cooperation of the State Highway Department of Indiana in planning and performing the field testing program. The rubber testing and polishing shoes were furnished by the Firestone Tire and Rubber Company. The work reported herein was performed as an activity of the Joint Highway Research Project of Purdue University with Mr. Morris Stewart in charge of the laboratory testing.

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